Effects of spectral bandpass on SeaWiFS-retrieved near-surface optical properties of the ocean

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A simple correction method to remove the spectral bandpass effects of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the derived normalized water-leaving radiances and ocean-near-surface chlorophyll concentration is developed and implemented in the SeaWiFS data-processing system. SeaWiFS has not only in-band response structures but also significant sensor out-of-band contributions. The effects of the SeaWiFS out-of-band contribution at the green bands is particularly significant for the derived normalized water-leaving radiances and therefore for the retrieved ocean-near-surface chlorophyll concentration. With the sensor spectral bandpass corrections, the low chlorophyll concentration is even lower in the clear ocean regions, whereas there are almost no changes for the oceans with a chlorophyll concentration of >0.2 mg/m^3. © 2001 Optical Society of America

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1. Introduction

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS),[1] which was successfully launched on 1 August 1997, is one of few satellite instruments that has complete prelaunch band spectral response measurements covering from 380 to 1150 nm for all eight SeaWiFS bands (with nominal center wavelengths at 412, 443, 490, 510, 555, 670, 765, and 865 nm). The SeaWiFS spectral bandwidth, which is defined as the full width at half-maximum (FWHM) of the response function, is 20 nm for the first six bands and 40 nm for the two near-IR bands. The in-band and out-of-band spectral responses are referred to as the spectral band response contributions from, respectively, within and outside the spectral bandwidth (FWHM). Figure 1 provides the spectral response function (SRF) for SeaWiFS bands 2, 3, and 5, respectively. We assume that the response functions of the SeaWiFS bands measured prelaunch are still valid on orbit. Obviously, SeaWiFS has not only in-band response structures but also significant sensor out-of-band contributions. This is particularly evident for the SeaWiFS 555-nm band in which there are significant out-of-band contributions from both the blue and the red wavelengths covering from approximately 400 to 480 nm and 630 to 730 nm, respectively. Although the magnitude of this out-of-band SRF is relatively small (maximum at ~0.4%), the effects on the derived water-leaving radiance at 555 nm and the chlorophyll concentration can be biased high for clear ocean waters (low chlorophyll concentration) because of the added ocean signals contributed by the blue wavelengths. Before the SeaWiFS third reprocessing in May 2000, biased high values in the SeaWiFS-derived chlorophyll concentration were observed when compared with *in situ* measurements in very clear (low chlorophyllconcentration) ocean regions.[2,3] For example, for a chlorophyll concentration of <0.1 mg/m^3, Fig. 1(d) in Ref. 2 shows biased high values from the SeaWiFS retrievals. In dealing with the SeaWiFS sensor out-of-band effects, we adopted a methodology[4] of estimating spectral bandpass effects for the individual contributions of the top of the atmosphere (TOA) radiance instead of the sensor-measured radiance itself. With a limited number of sensor-measured spectral radiances, it is difficult to estimate accurately the sensor out-of-band effects from the TOA radiances since it involves unknown spectral contributions that need to be resolved in remote retrieval processing. In this paper, we describe our efforts in studying the effects of the SeaWiFS spectral bandpass on the retrieved normalized

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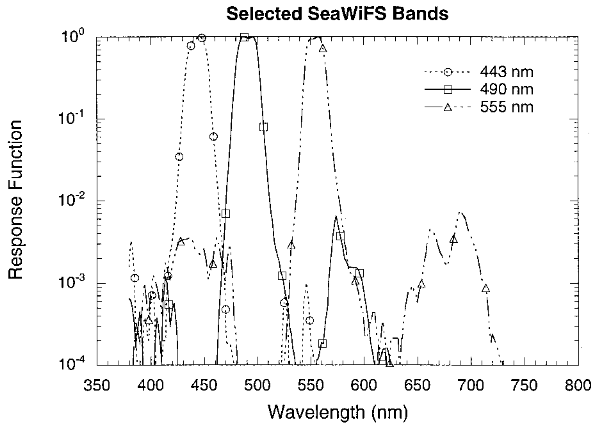


Fig. 1. SeaWiFS spectral response functions for SeaWiFS bands 2 (443 nm), 3 (490 nm), and 5 (555 nm).

water-leaving radiances and ocean near-surface chlorophyll concentrations. We quantitatively estimate the SeaWiFS SRF effects on the retrieved ocean optical products, propose a method to correct them, and outline its implementation in the SeaWiFS data-processing system. Therefore the SeaWiFS results can be compared in a more meaningful way with the *in situ* measurements.

2. Background

In ocean-color remote sensing, the sensor-measured radiance at the top of the ocean–atmosphere system, measured at wavelength λ, can be written as

$$L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + t(\lambda)L_{wc}(\lambda) + t(\lambda)L_w(\lambda), \quad (1)$$

where $L_r(\lambda)$, $L_a(\lambda)$, and $L_{ra}(\lambda)$ are contributions, respectively, from the multiple scattering of air molecules (Rayleigh scattering with no aerosols), aerosols (no air molecules), and Rayleigh–aerosol interactions.[5] The $L_{wc}(\lambda)$ is the radiance at the sea surface that arises from sunlight and skylight reflecting from whitecaps on the surface.[6–8] The $L_w(\lambda)$ is the water-leaving radiance that is the desired quantity in ocean-color remote sensing to relate the ocean near-surface physical and bio-optical properties and $t(\lambda)$ is the atmospheric diffuse transmittance that accounts for the effects of propagating $L_w(\lambda)$ and $L_{wc}(\lambda)$ from the sea surface to the TOA. Note that, in Eq. (1), the surface sun glint term has been ignored because there are usually no meaningful retrievals in regions significantly contaminated by sun glint. The measurement of radiances affected by sun glint have to be avoided and/or masked out. Because of the sensor spectral bandpass, the radiance measured by SeaWiFS is a band-averaged value weighted by the sensor SRF. We define

$$\langle L(\lambda_i)\rangle = \frac{\int L(\lambda)S_i(\lambda)\mathrm{d}\lambda}{\int S_i(\lambda)\mathrm{d}\lambda}, \quad (2)$$

where $S_i(\lambda)$ is the SeaWiFS SRF for band i at a nominal center wavelength λ_i. By applying Eq. (2) to both sides of Eq. (1), one can rewrite Eq. (1) as

$$\langle L_t(\lambda_i)\rangle = \langle L_r(\lambda_i)\rangle + \langle L_a(\lambda_i) + L_{ra}(\lambda_i)\rangle + \langle t(\lambda_i)L_{wc}(\lambda_i)\rangle + \langle t(\lambda_i)L_w(\lambda_i)\rangle, \quad (3)$$

where i = 1–8 corresponds to the SeaWiFS eight spectral bands. Therefore the SeaWiFS measurements are governed by the radiative-transfer equation as Eq. (3) in the ocean–atmosphere system. In Eq. (3) $\langle L_t(\lambda_i)\rangle$ is the SeaWiFS measured radiance at the TOA. The band-averaged Rayleigh contribution $\langle L_r(\lambda_i)\rangle$ can be computed with the band-averaged Rayleigh optical thickness (weighted by the band SRF and the extraterrestrial solar irradiance) and average solar irradiance (weighted by the band SRF).[4] The band-averaged whitecap radiance contributions can be approximated at the SeaWiFS nominal center wavelengths, i.e.,

$$\langle t(\lambda_i)L_{wc}(\lambda_i)\rangle \approx t'(\lambda_i)L_{wc}(\lambda_i), \quad (4)$$

where $t'(\lambda_i)$ is the diffuse transmittance computed with the band-averaged Rayleigh and ozone optical thicknesses as weighted by the sensor band SRF and the extraterrestrial solar irradiance[4,9] and $L_{wc}(\lambda_i)$ can be estimated by the models with the input of the sea-surface wind speed.[6–8] The $L_{wc}(\lambda_i)$ model uncertainty is usually much larger than the error introduced in approximation (4). The computation of $\langle L_a(\lambda_i) + L_{ra}(\lambda_i)\rangle$, however, is complicated by the characteristic of the aerosol optical properties being unknown. Gordon[4] outlined a methodology for dealing with the SeaWiFS spectral bandpass effects on the evaluations of aerosol and Rayleigh–aerosol interaction contributions. The SeaWiFS atmospheric correction algorithm[5] can then be executed. It was shown that, using the definition of the normalized water-leaving radiance,[10] $[L_w(\lambda_i)]_N$, i.e.,

$$L_w(\lambda_i) = \cos\theta_0 t_0(\lambda_i)[L_w(\lambda_i)]_N,$$

the last term in Eq. (3) can be approximated as[4]

$$\langle t(\lambda_i)L_w(\lambda_i)\rangle \approx t'(\lambda_i)t_0'(\lambda_i)\cos\theta_0\langle[L_w(\lambda_i)]_N\rangle, \quad (5)$$

where $t_0'(\lambda_i)$ and $t'(\lambda_i)$ are the atmospheric diffuse transmittance at, respectively, the solar and the sensor-viewing directions computed by the band-averaged Rayleigh and ozone optical thicknesses as weighted by the sensor band SRF and the extraterrestrial solar irradiance. Therefore before the SeaWiFS's third reprocessing in May 2000, the SeaWiFS routinely reported the band-averaged normalized water-leaving radiances and used ratios of these values to relate the ocean near-surface chlorophyll concentrations.[11] To validate the SeaWiFS ocean-color products, however, one needs to compare the SeaWiFS retrieved normalized water-leaving radiances with those from the *in situ* measurements, which are often acquired at the SeaWiFS nominal center wavelengths with instruments with very narrow bandpasses. Furthermore the SeaWiFS bio-optical

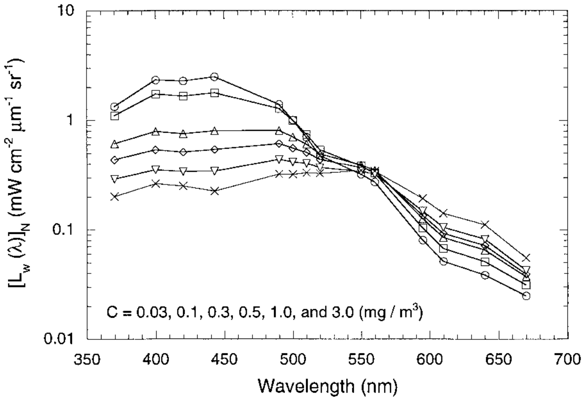


Fig. 2. Spectral distribution of the normalized water-leaving radiance $[L_w(\lambda)]_N$ for typical case 1 water for pigment concentration of (from top to bottom) 0.03, 0.1, 0.3, 0.5, 1.0, and 3.0 (mg/m^3). These are derived from Gordon *et al.*[12]

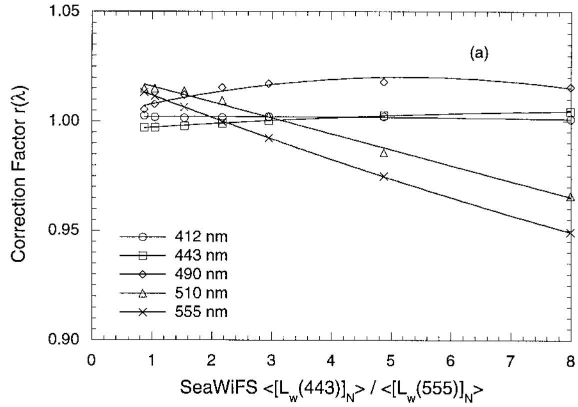
algorithm[11] was derived with the *in situ* data that were measured in a very narrow bandpass as at approximately the SeaWiFS nominal band center wavelengths. They are usually different from the SeaWiFS band-averaged values.

3. Effects of Spectral Bandpass on $[L_w(\lambda_i)]_N$

To assess the effects of the SeaWiFS spectral band responses on the derived normalized water-leaving radiance when comparing the results derived from the nominal center wavelengths, we need to compute the value of $\langle[L_w(\lambda_i)]_N\rangle$. Therefore the spectral distribution of $[L_w(\lambda)]_N$ with various pigment concentration values is needed. Figure 2 provides typical $[L_w(\lambda)]_N$ (case 1 water) spectral distributions obtained from bio-optical model calculations[12] for six phytoplankton pigment concentration values, C = 0.03, 0.1, 0.3, 0.5, 1.0, and 3.0 (mg/m^3). We have used $[L_w(\lambda)]_N$ values as shown in Fig. 2 to compute $\langle[L_w(\lambda_i)]_N\rangle$ and estimate the difference between $\langle[L_w(\lambda_i)]_N\rangle$ and $[L_w(\lambda_i)]_N$. For a given SeaWiFS spectral band in the visible a correction factor $r(\lambda_i)$ can be defined as

$$r(\lambda_i) = [L_w(\lambda_i)]_N/\langle[L_w(\lambda_i)]_N\rangle. \tag{6}$$

Obviously, the correction factor $r(\lambda_i)$ depends on the ocean pigment concentration. Figure 3 provides $r(\lambda_i)$ values as a function of the SeaWiFS-derived ratio values in the normalized water-leaving radiances between two bands. Figure 3(a) is for the case of ratios between SeaWiFS bands 2 and 5, while Fig. 3(b) is for the ratios between bands 3 and 5. They were generated with the spectral distribution of $[L_w(\lambda)]_N$ from Gordon *et al.*[12] and for pigment concentrations of 0.03, 0.1, 0.2, 0.3, 0.5, 1.0, and 1.5 (mg/m^3). A low ratio value corresponds to a high pigment concentration. The curves in Fig. 3 are the least-squares fit for the computed data for SeaWiFS bands 1–5. Table 1 provides least-squares fitting coefficients for SeaWiFS bands 1–5 in Fig. 3. The



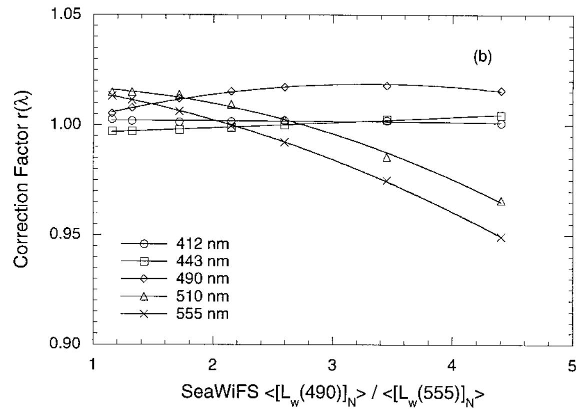


Fig. 3. Spectral bandpass correction factor $r(\lambda_i)$ for SeaWiFS bands 1–5 as a function of the SeaWiFS-derived two-band ratio values in the normalized water-leaving radiances between (a) bands 2 and 5 and (b) bands 3 and 5. The data correspond to pigment concentrations of 0.03, 0.1, 0.2, 0.3, 0.5, 1.0, and 1.5 (mg/m^3), respectively, from high to low ratio values. The curves are the least-squares fit.

coefficients were derived as least-squares fit for data $r(\lambda_i)$ versus $\langle[L_w(\lambda_j)]_N\rangle/\langle[L_w(\lambda_k)]_N\rangle$, i.e.,

$$r(\lambda_i) = a_0^{(j,k)}(\lambda_i) + a_1^{(j,k)}(\lambda_i)\{\langle[L_w(\lambda_j)]_N\rangle/\langle[L_w(\lambda_k)]_N\rangle\} + a_2^{(j,k)}(\lambda_i)\{\langle[L_w(\lambda_j)]_N\rangle/\langle[L_w(\lambda_k)]_N\}^2, \tag{7}$$

where $a_0^{(j,k)}(\lambda_i)$, $a_1^{(j,k)}(\lambda_i)$, and $a_2^{(j,k)}(\lambda_i)$ are the fitting coefficients for the correction factor for SeaWiFS band λ_i when the two-band ratio value of the SeaWiFS-derived normalized water-leaving radiances at wavelengths λ_j and λ_k is used. Note that, to compute the required integrals for the SeaWiFS $\langle[L_w(\lambda_i)]_N\rangle$ values, a log–linear interpolation was used for other wavelengths covering the SeaWiFS SRF from 380 to 1150 nm. Results show that there are almost no spectral bandpass effects for SeaWiFS bands 1 and 2 [$r(\lambda_i) \approx 1$]. When compared with the $[L_w(\lambda_i)]_N$ values, the SeaWiFS derived $\langle[L_w(\lambda_i)]_N\rangle$ at band 3 has been slightly underestimated [$r(\lambda_i) > 1$], whereas the values derived at bands 4 and 5 are overestimated [$r(\lambda_i) < 1$] for the clean ocean cases, e.g., approximately 3.5% and 5% biased high, respectively, for a pigment concentration of ~0.03 (mg/m^3). Similar results were obtained by Gordon.[4] This

Table 1. Values of the Least-Squares Fitting Coefficients for SeaWiFS Bands 1–5 in Figs. 3(a) and 3(b)

Wavelength (nm)	Fitting Coefficients [Fig. 3(a)]			Fitting Coefficients [Fig. 3(b)]		
	$a_0^{(2,5)}(\lambda)$	$a_1^{(2,5)}(\lambda)$	$a_2^{(2,5)}(\lambda)$	$a_0^{(3,5)}(\lambda)$	$a_1^{(3,5)}(\lambda)$	$a_2^{(3,5)}(\lambda)$
412	1.0019	5.288×10^{-5}	-1.987×10^{-5}	1.0019	1.849×10^{-4}	-8.819×10^{-5}
443	0.9952	1.953×10^{-3}	-1.003×10^{-4}	0.9939	2.471×10^{-3}	-3.350×10^{-5}
490	1.0022	6.289×10^{-3}	-5.402×10^{-4}	0.9891	1.741×10^{-2}	-2.560×10^{-3}
510	1.0238	-7.906×10^{-3}	1.097×10^{-4}	1.0189	1.073×10^{-3}	-2.901×10^{-3}
555	1.0222	-1.067×10^{-2}	1.851×10^{-4}	1.0206	-3.063×10^{-3}	-3.007×10^{-3}

leads to an overestimation of the SeaWiFS-derived chlorophyll concentration for the very clean (low chlorophyll concentration) open ocean waters.

4. Corrections of SeaWiFS Spectral Bandpass Effects

There are two alternatives for resolving the inconsistency between the SeaWiFS $\langle[L_w(\lambda_i)]_N\rangle$ and $[L_w(\lambda_i)]_N$ values: (1) $[L_W(\lambda_i)]_N$ data are required to be converted to $\langle[L_w(\lambda_i)]_N\rangle$ by all investigators who make *in situ* measurements and a bio-optical algorithm needs to be rederived with $\langle[L_w(\lambda_i)]_N\rangle$ values, and (2) to convert SeaWiFS $\langle[L_w(\lambda_i)]_N\rangle$ to $[L_w(\lambda_i)]_N$ values. The first option is much more involved. Here we describe the second approach.

To convert $\langle[L_w(\lambda_i)]_N\rangle$ to $[L_w(\lambda_i)]_N$ at the SeaWiFS spectral bands, one needs the spectral distribution of $[L_w(\lambda)]_N$, which depends on the ocean near-surface optical and microphysical properties. With the SeaWiFS derived $\langle[L_w(\lambda_i)]_N\rangle$ at the six visible spectral bands, one could correct the spectral bandpass effects by using an iteration method[3] in which the bio-optical model is not required. However, in SeaWiFS operational data processing, it is more efficient to use the precomputed tables as shown in Fig. 3 for corrections from inputs of the SeaWiFS-derived two-band ratio values. For this approach, however, a reasonable ocean bio-optical model is needed.

To understand the sensitivity of the correction factor $r(\lambda_i)$ with the variation in the ocean bio-optical model, studies were conducted for various values of a scattering-related parameter b^0 in the Gordon *et al.*[12] model. Gordon and Morel[13] summarized various *in situ* measurements and found that, for a given pigment concentration C in milligrams per cubic meter, b^0 varies from 0.12 to 0.45 m^{-1} with a mean value of 0.3 m^{-1}. In all $[L_w(\lambda_i)]_N$ computations thus far, b^0 of 0.3 m^{-1} were used. For the case of $C = 0.03$ mg/m^3 and b^0 of 0.12 and 0.45 m^{-1} the model predicts the normalized water-leaving radiance in 443-nm ranges from approximately 2 to 3 (mW cm^{-2} μm^{-1} sr^{-1}), while at 550 nm $[L_w(\lambda_i)]_N$ varies from approximately 0.23 to 0.40 (mW cm^{-2} μm^{-1} sr^{-1}). They represent 50% and 70% changes. Figure 4 provides results of the correction factor $r(\lambda_i)$ as a function of the pigment concentration for b^0 values of 0.12, 0.30, and 0.45 m^{-1}, which were used in computing $[L_w(\lambda_i)]_N$ for SeaWiFS wavelengths of 443 and 555 nm. As expected, results show that there is almost no difference in $r(\lambda_i)$ for various b^0 values at 443 nm, while there are small differences at 555 nm. For $C = 0.03$ mg/m^3, values of $r(555)$ are 0.941, 0.949, and 0.953 corresponding to b^0 of 0.12, 0.30, and 0.45 m^{-1}, respectively. This represents a maximum of 0.8% model uncertainty in $r(\lambda_i)$ computation at 555 nm for very clear open oceans.

The implementation of such a correction scheme for the spectral bandpass effects in the SeaWiFS data-processing system is straightforward: (1) First, the correction tables $r(\lambda_i)$ as a function of the SeaWiFS-derived two-band $\langle[L_w(\lambda_i)]_N\rangle$ ratios can be computed with an ocean bio-optical model (e.g., Fig. 3), and coefficients for the least-squares fit are then derived as in Table 1. (2) Next, with the SeaWiFS derived $\langle[L_w(\lambda_i)]_N\rangle$ and corresponding two-band ratio values between two visible bands, the spectral bandpass correction factor $r(\lambda_i)$ can be computed from Eq. (7). In the SeaWiFS case the two-band ratio values in the derived $\langle[L_w(\lambda_i)]_N\rangle$ between bands 3 (490 nm) and 5 (555 nm) are used. (3) Finally, the normalized water-leaving radiance at the SeaWiFS nominal band center $[L_w(\lambda_i)]_N$ can be derived, i.e.,

$$[L_w(\lambda_i)]_N = r(\lambda_i)\langle[L_w(\lambda_i)]_N\rangle. \tag{8}$$

These corrected normalized water-leaving radiance values $[L_w(\lambda_i)]_N$ can then be used to derive the ocean chlorophyll-a concentrations. The correction of the SeaWiFS spectral bandpass effects is important for

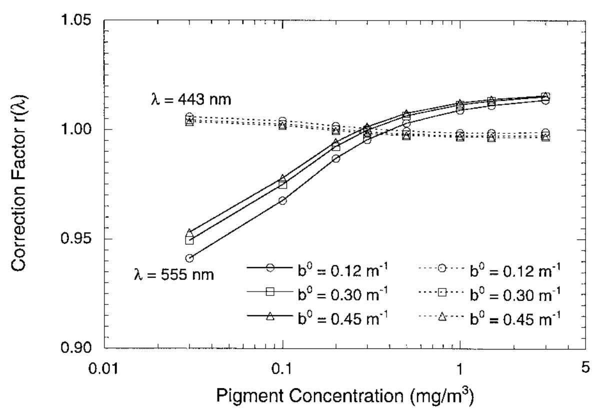


Fig. 4. Correction factor $r(\lambda_i)$ as a function of the pigment concentration for b^0 values of 0.12, 0.30, and 0.45 m^{-1} for SeaWiFS wavelengths of 443 and 555 nm.

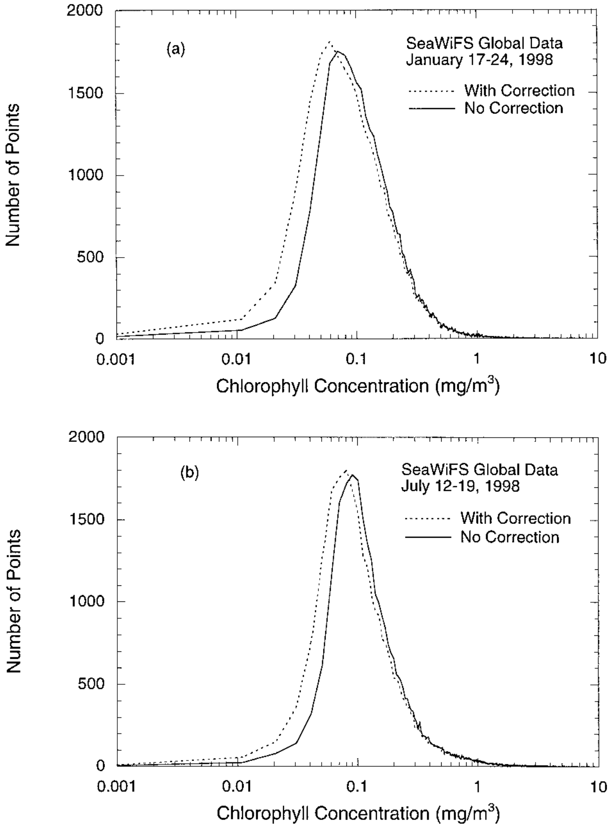


Fig. 5. Histograms of the SeaWiFS-retrieved chlorophyll concentrations for cases with and without spectral bandpass corrections for the eight-day global data for the case of (a) winter (17–24 January 1998) and (b) summer (12–19 July 1998), respectively.

the SeaWiFS-derived normalized water-leaving radiance at the green–red bands in clear open ocean waters (low chlorophyll concentration).

5. Results

The correction scheme of the spectral bandpass effects has been implemented in the SeaWiFS data-processing system and extensively tested with the SeaWiFS global measurements. Figure 5 provides an example of the histograms of the SeaWiFS-derived chlorophyll concentration values for cases with and without spectral bandpass corrections for the SeaWiFS eight-day global data in the winter (17–24 January 1998) and summer (12–19 July 1998), respectively. In deriving chlorophyll concentration values, the bio-optical algorithm of ocean chlorophyll 2 version 2[11] (OC2v2) was used. For cases of both with and without spectral bandpass correction, the curve shapes of the histogram are similar. However, with the correction, the curve (chlorophyll concentration) is shifted slightly at the low end, i.e., to lower concentrations, whereas there is little change for cases of chlorophyll concentration of >0.2 mg/m^3. These results are consistent with a study by Wang *et al.*[3] for both simulated and *in situ* matchup analyses. In Fig. 5 the seasonal variation of the global chlorophyll concentration distribution is quite obvious (the global ocean in winter is clearer than that of summer) partly because of El Niño and La Niño phenomena in 1997–1998.[14]

6. Conclusions

We have carried out a study to analyze the effects of the SeaWiFS spectral bandpass on the retrieved normalized water-leaving radiance and the ocean chlorophyll concentration. It was found that, for very clear ocean waters (with low chlorophyll concentration), the effects of the out-of-band contributions were small for the SeaWiFS blue bands, whereas at the SeaWiFS green bands there was an $\sim$5% overestimation in the derived normalized water-leaving radiance compared with that of the SeaWiFS nominal center wavelengths. This leads to an overestimation of the derived ocean near-surface chlorophyll concentration in clear open ocean regions. A simple sensor spectral bandpass correction scheme was developed and implemented into the SeaWiFS data-processing system. With the spectral bandpass corrections the low chlorophyll concentration is even lower in clear open oceans, while there is almost no change for cases of chlorophyll concentration of >0.2 mg/m^3. This study demonstrates the importance and necessity of having complete prelaunch sensor spectral response measurements for ocean-color remote sensing. Furthermore, to compare the ocean-color products derived from two different sensors, the effects of the differences in the sensor spectral band responses need to be considered.

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